PCT/GB 2002/005930

10 Rec'd PCT/PTC 28 JUN 2004

The Patent Office

PATENTS • DESIGNS • COPYRIGHT • TRADE MARKS

10/500318

INVESTOR IN PEOPLE

10 Rec'd PCT/PTC 28 JUN 2004

PRIORITY DOCUMENT

SUBMITTED OR TRANSMITTED IN COMPLIANCE WITH RULE 17.1(a) OR (b)

The Patent Office
Concept House
Cardiff Road
Newport
South Wales
NP10 8QQ

RECEIVED 07 FEB 2003
WIPO PCT

I, the undersigned, being an officer duly authorised in accordance with Section 74(1) and (4) of the Deregulation & Contracting Out Act 1994, to sign and issue certificates on behalf of the Comptroller-General, hereby certify that annexed hereto is a true copy of the documents as originally filed in connection with the patent application identified therein.

In accordance with the Patents (Companies Re-registration) Rules 1982, if a company named in this certificate and any accompanying documents has re-registered under the Companies Act 1980 with the same name as that with which it was registered immediately before re-registration save for the substitution as, or inclusion as, the last part of the name of the words "public limited company" or their equivalents in Welsh, references to the name of the company in this certificate and any accompanying documents shall be treated as references to the name with which it is so re-registered.

In accordance with the rules, the words "public limited company" may be replaced by p.l.c., plc, P.L.C. or PLC.

Re-registration under the Companies Act does not constitute a new legal entity but merely subjects the company to certain additional company law rules.

Signed

Dated 28 January 2003

Patents Form 1/77

Patents Act 1977
(Rule 16)

The Patent Office

THE PATENT OFFICE
M
27 DEC 2001
RULE 97
NEWPORT

1/77

28DEC01 E684604-1 D02813
P01/7700 0.00-0131001.0

Request for grant of a patent

(See the notes on the back of this form. You can also get an explanatory leaflet from the Patent Office to help you fill in this form)

The Patent Office
Cardiff Road
Newport
South Wales
NP9 1RH

1.	Your Reference	P51046u GB
2.	Patent Application number *(The Patent Office will fill in this part)*	**0131001.0** 27 DEC 2001
3.	Full name, address and postcode of the or each applicant *(underline all surnames)*	Bookham Technology plc 90 Milton Park Abingdon Oxon OX14 4RY
	Patents ADP Number *(if you know it)*	
	If the applicant is a corporate body, give the country/state of its incorporation	England & Wales 07909757001
4.	Title of the invention	A Photodiode
5.	Name of your agent *(if you have one)*	Fry Heath & Spence LLP
	"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	The Old College 53 High Street Horley, Surrey RH6 7BN
	Patents ADP Number *(if you know it)*	05880273001

		Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*
6.	If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or each of these earlier applications and *(if you know it)* the or each application number.			

		Number of earlier application	Date of filing *(day / month / year)*
7.	If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application.		

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:* — Yes

a) any applicant named in part 3 is not an inventor; or

b) there is an inventor who is not named as an applicant, or

c) any named applicant is a corporate body.

(See note (d))

9. Enter the number of sheets for any of the following items you are filing with this form. Do not count copies of the same document.

Continuation sheets of this form	
Description	8
Claim(s)	3
Abstract	0
Drawing(s)	2 + 2

10. If you are also filing any of the following, state how many against each item.

Priority documents	xxx
Translations of priority documents	xxx
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	~~yes~~
Request for preliminary examination and search *(Patents form 9/77)*	yes
Request for substantive examination *(Patents form 10/77)*	xxx
Any other documents *(please specify)*	xxx

11. I/We request the grant of a patent on the basis of this application.

Signature S.G.U

Date 24 December 2001

12. Name and daytime telephone number of person to contact in the United Kingdom — S. G. Unwin, 01865 841060

Warning

After an application for a patent has been filed, the Comptroller of the Patent Office will consider whether publication or communication of the invention should be prohibited or restricted under Section 22 of the Patents Act 1977. You will be informed if it is necessary to prohibit or restrict your invention in this way. Furthermore, if you live in the United Kingdom, Section 23 of the Patents Act 1977 stops you filing or applying for a patent abroad without first getting written permission from the Patent Office unless an application has been filed at least 6 weeks beforehand in the United Kingdom for a patent for the same invention and either no direction prohibiting publication or communication has been given, or any such direction has been revoked.

Notes

a) *If you need help to fill in this form or you have any questions, please contact the Patent Office on 0645 500505.*

b) *Write your answers in capital letters using black ink or you may type them.*

c) *If there is not enough space for all the relevant details on any part of this form, please continue on a separate sheet of paper and write "see continuation sheet" in the relevant part(s). Any continuation sheet should be attached to this form.*

d) *If you have answered 'Yes' Patents Form 7/77 will need to be filed.*

e) *Once you have filled in the form you must remember to sign and date it.*

f) *For details of the fee and ways to pay please contact the Patent Office.*

A PHOTODIODE

The present invention relates to a photodiode and, in particular, a photodiode fabricated so as to sense optical signals of a selected wavelength or wavelength band.

Discrete silicon based p-i-n photodiodes are used in the opto-electronics industry. Their efficiency is greatest in the wavelength region 0.6-0.8 microns which corresponds to the energy band-gap of silicon.

Silicon based optical circuits are now being produced and these require photodiodes for sensing optical signals within the circuits. To date, such photodiodes have been formed of other materials, e.g. InGaAs/Ge, which are capable of sensing the wavelengths of 1.3 and 1.5 microns commonly used in opto-communication devices and/or are of such a construction that the diode has to be hybridised with the silicon circuits, i.e. mounted thereon as a separate component.

The present invention provides an alternative form of photodiode for use in optical circuits.

According to a first aspect of the invention, there is provided a photodiode comprising a p-i-n diode formed in a semiconductor substrate having an energy band gap the magnitude of which corresponds to absorption of photons of a first wavelength, the photodiode comprising a substantially intrinsic region formed in said semiconductor substrate between p- and n-doped regions, the intrinsic region being modified to introduce deep band gap levels therein so as to provide at least partial absorption of photons of an optical signal of a selected wavelength or wavelength band greater than said first wavelength and thus generate an electrical signal across the p-i-n diode indicative of said optical signal.

Preferably, the semiconductor substrate is silicon in which case the photodiode can be integrated within a silicon-based integrated optical circuit. The need to hybridise photodiodes made of other semiconductor materials onto a silicon substrate is thus avoided.

Preferably, the deep band gap levels are provided by ion implantation as this method allows precise control of the depth and concentration of the deep band gap states so the wavelength and amount of light absorbed can be tightly controlled.

Other preferred and optional features of the invention will be apparent from the following description and from the subsidiary claims of the specification.

Deep band gap states referred to herein are states between the valence band and conduction band of the semiconductor material but spaced therefrom by a sufficient energy gap such that thermal excitation of electrons from the valence band to the deep band gap state or from the deep band gap state to the conductive band is small (so the dark current of the device is low). It will be appreciated that the magnitude of this energy gap will depend upon the temperature of the device, and, whilst the present invention is not limited to temperature, it is primarily directed towards devices designed to operate in the temperature range of 0 to 100 degrees Centigrade.

The invention will now be further described, merely by way of example, with reference to the accompanying drawings, in which:-

Figure 1 is a schematic, cross-sectional view of a photodiode according to one embodiment of the invention;

Figure 2 is a band-gap diagram illustrating the operation of a photodiode such as that shown in Figure 1; and

Figures 3A to 3F illustrates steps in a preferred method of fabricating a photodiode such as that shown in Figure 1.

Figure 1 shows a schematic, cross-sectional view of a p-i-n photodiode formed in a silicon substrate. In the example shown, the silicon substrate comprises a silicon-on-insulator chip having a silicon light conducting layer 1 separated from a substrate 2, which is also typically of silicon, by a light confining layer 3, e.g. of silicon dioxide.

A rib 4 is formed in the silicon layer 1 so as to form a rib waveguide therein. The approximate position of the optical mode within this waveguide is illustrated by the dashed line 5.

Recesses 1A and 1B are preferably formed in the silicon layer 1 and n- and p-doped regions 6 and 7 formed in the silicon layer 1 by doping through these recesses. Electrical contacts 8 and 9 connect the n- and p- doped regions to an electrical circuit 10 arranged to provide a reverse bias between the n- and p- doped regions.

Other doping arrangements are possible, e.g. without the recesses 1A and 1B (see Figure 3) or side-doped arrangements as described in WO 00/10039.

The layer 1 of silicon between the n- and p-doped regions is substantially intrinsic so this arrangement forms a p-i-n diode across the rib waveguide. However, the intrinsic region is modified to introduce deep band gap levels therein as indicated by the Xs in region 11 of Figure 1. These levels can be excited by sub-band-gap photons so producing free charge carriers and thus a measurable electrical signal in the circuit 10 upon application of a voltage across the p-i-n diode.

Deep band gap levels can be introduced by ion implantation which can give rise to free charge carriers in several ways:

(i) ion implantation and subsequent activation by heat treatment of deep-level impurities, e.g. gold, oxygen or carbon atoms. The heat treatment typically involves heating to 650-1000 degrees C for several seconds. The impurity atoms occupy sites in the crystal lattice and the electrons associated therewith form the deep band gap states. The heat treatment re-crystallises the silicon to repair the damage caused by the implantation of the impurities.

(ii) ion implantation induced defects in doped material, the defects resulting from the implantation of non-dopant atoms such as silicon, helium or hydrogen. Charge carriers will be trapped in the deep-gap defect states and released to the conduction band upon illumination by light of the appropriate wavelength.

(iii) ion implantation induced defects (in the crystalline structure) in the intrinsic material. In this case, charge carriers may be excited into the deep-gap states upon illumination by light of the appropriate wavelength and then undergo "hopping" conduction from defect to defect.

The formation of deep band gap levels and the mechanisms by which they give rise to free charge carriers are known so need not be described in greater detail.

As discussed above, deep band gap levels produced by each of these methods should be deep enough to provide a low dark-current, i.e. no signal or only a very low signal is produced when the defects are not illuminated as thermal excitation of carriers is too low to produce enough free charge carriers to give rise to a significant electrical current.

The use of ion implantation to form the deep band gap levels allows precise control of their depth and concentration so the amount of light absorbed can be tightly controlled. In the illustrated example, the deep band gap levels are formed at a depth which corresponds with the location of the optical mode 5 so as to maximise the interaction therewith. However, in other arrangements the deep band gap levels may be located so as to interact with only part of the optical mode.

Figure 2 is a band-gap diagram illustrating operation of the device. The lines 20 and 21 represent the energy levels of the band gap from the p-doped region to the n-doped region when the p-i-n diode is under reverse bias. The Xs again represent the deep band gap levels and are located in the intrinsic region between the band-gap energy levels. Charge carriers absorbing incoming photons (indicated by hν) can be excited from the lower energy level 20 to the deep-sub-band-gap levels as indicated by vertical arrow 22A and then take part in hopping conduction. Alternatively, carriers absorbing incoming photons can be excited from the deep-sub-band-gap levels to the upper energy level 21 as indicated by vertical arrow 22B.

A p-i-n photodiode such as that described in relation to Figure 1 can be integrated with an optical circuit formed on the silicon-on-insulator chip thus avoiding the need to hybridise a photodiode onto the silicon chip.

Figures 3A-3F illustrate a method by which a photodiode such as that described above may be fabricated.

Figure 3A illustrates a rib 4 etched in the silicon layer 1 of a silicon-on-insulator chip.

Figure 3B shows the formation of p-and n-doped regions 6 and 7 by conventional doping techniques.

A mask 30, e.g. of silicon dioxide is then formed over the device and a window 31 formed in the mask to expose the upper surface of rib 4 as shown in Figure 3C.

Figure 3D illustrates the ion implantation step through the window 31 in the mask 30. Ions such as Si^+, He^+ or H^+ may be implanted to create damage in the crystalline silicon layer 1. Such damage in turn creates deep-sub-band-gap states allowing subsequent detection of deep-sub-band-gap light as described by mechanisms (ii) and (iii) above. Alternatively, ions such as Au^+, O^+ or C^+ may be implanted. These ions, once electrically activated create deep-sub-band-gap states allowing subsequent detection of deep-sub-band-gap light as described in mechanism (i) above.

The mask 30 is then removed and the device thermally treated to either engineer the defect structure (in the case of, e.g., Si^+, He^+ or H^+ implantation) or electrically activate the deep electrical dopants (in the case of, e.g., Au^+, C^+ or O^+ implantation). In the case of defect engineering, this typically involves heat treatment at temperatures between 25 and 800 degrees C for several seconds. In the case of electrical activation, this will typically involve heat treatment at temperatures between 650 and 1000 degrees C for several minutes. The deep-sub-band gap defects thus produced are indicated by Xs in Figure 3E.

Finally, electrical contacts 8 and 9 are formed and the device connected to an electrical circuit 10 as shown in figure 3F.

As discussed above, when an optical signal of a selected wavelength or wavelength band, in this case the 1.3 and 1.5 micron bands commonly used in opto-communication applications, is transmitted along the rib waveguide an electrical signal is generated by charge carriers moving either to or from the deep-sub-band-gap levels either to or from the conduction valance bands as

illustrated in Figure 2 which can be detected by the electrical circuit 10 to provide an output indicative of said optical signal.

A photodiode capable of detecting photons of a wavelength greater than that corresponding to the band gap of silicon can thus be provided by forming defects in the intrinsic region of a p-i-n photodiode and engineering these defects to provide deep-sub-band-gap levels in the intrinsic region.

The deep-sub-band-gap levels may be formed in various ways. As mentioned above, this may comprise the introduction of electrical impurities such as gold, oxygen or carbon atoms. Or it may comprise forming defects in the silicon itself, e.g. caused by the implantation or bombardment of the silicon by hydrogen, helium or silicon atoms.

Other geometric arrangements of the p-i-n photodiode structure may also be used. Figure 1 illustrates a lateral p-i-n photodiode formed across a rib waveguide. A vertical p-i-n structure may also be used, e.g. by forming p-doped regions on each side of the waveguide and an n-doped region on the top of the rib of the waveguide, or vice versa. In some cases, a longitudinal p-i-n diode may also be used.

The p-i-n photodiode structure may also be used in relation to other types of waveguide or in any arrangement in which the light to be sensed is incident thereon, e.g. at the end of a waveguide or on an area of the chip exposed to an external light source or within a resonant cavity.

The dimensions of the rib waveguide are typically in the range of 2-20 microns. The charge carriers generated within the photodiode therefore only need to be swept over relatively short distance, e.g. 10 microns or less or preferably 5 microns or less, before being detected by the p- or n-doped regions.

The deep-sub-band gap levels may also be formed at any position or positions within the intrinsic region. For instance, instead of being centrally located as shown in Figure 3F they may be located either side of the region, e.g. in the slab regions between the rib 4 and the doped regions 6 and 7.

The nature of the arrangements described above also allow the photodiode to be fabricated easily and extremely accurately and for its properties to be carefully tailored to suit the application. The energy levels of the deep band gap levels can be accurately determined as well as their location within the device.

Also, whilst the invention has been described above in relation to the p-i-n photo-diode formed in silicon, the invention can also be applied to other semiconductor material in which deep band gap levels can be introduced to enable wavelengths longer than that associated with the band gap of the material to be detected.

Further aspects of the photodiode described herein are described and claimed in the applicant's co-pending application GB............. entitled "A Light Sensor" filed on the same day as this application and the disclosure thereof is incorporated herein.

CLAIMS

1. A photodiode comprising a p-i-n diode formed in a semiconductor substrate having an energy band gap the magnitude of which corresponds to absorption of photons of a first wavelength, the photodiode comprising a substantially intrinsic region in said semiconductor substrate between p- and n-doped regions, the intrinsic region being modified to introduce deep band gap levels therein so as to provide at least partial absorption of photons of an optical signal of a selected wavelength or wavelength band greater than said first wavelength and thus generate an electrical signal across the p-i-n diode indicative of said optical signal.

2. A photodiode as claimed in Claim 1 in which the intrinsic region is modified by ion implantation.

3. A photodiode as claimed in Claim 1 or 2 in which the modification comprises defects in the intrinsic region.

4. A photodiode as claimed in Claim 3 in which the defects comprise defects in the crystalline structure of the intrinsic region itself.

5. A photodiode as claimed in Claim 3 or 4 in which the defects comprise elemental impurities.

6. A photodiode as claimed in any preceding claim in which the intrinsic region forms part of a waveguide.

7. A photodiode as claimed in Claim 6 in which the deep band gap levels are located so as to maximise their interaction with light transmitted along the waveguide.

8. A photodiode as claimed in Claim 6 or 7 in which the waveguide is a rib waveguide.

9. A photodiode as claimed in Claim 8 in which the p-and n-doped regions are formed on opposite sides of the rib waveguide.

10. A photodiode as claimed in Claim 8 in which the p-doped region is formed on one side or both side of the rib waveguide and the n-doped region on top of the rib waveguide, or vice versa.

11. A photodiode as claimed in any preceding claim in which the substrate is silicon.

12. A photodiode as claimed in Claim 11 in which the substrate is a silicon-on-insulator chip.

13. A photodiode as claimed in any preceding claim in which the selected wavelength band is around 1.3 or 1.5 microns.

14. A method of fabricating a photodiode comprising the steps of:

forming p-and n-doped regions in a substrate having an energy band gap the magnitude of which corresponds to absorption of photons of a first wavelength with a substantially intrinsic region therebetween;

modifying the intrinsic region to introduce deep band gap levels therein so as to provide at least partial absorptions of photons of selected wavelength or wavelength band greater than said first wavelength.

15. A method as claimed in Claim 14 in which the modifying of the intrinsic region is by ion implantation.

16. A method as claimed in claim 15 in which one or more of the following species is implanted: gold, oxygen, carbon, hydrogen, helium, and silicon atoms.

17. A photodiode substantially as thereinbefore described with reference to and/or as shown in one or more of the accompanying drawings.

18. A method of fabricating a photodiode substantially as hereinbefore described.

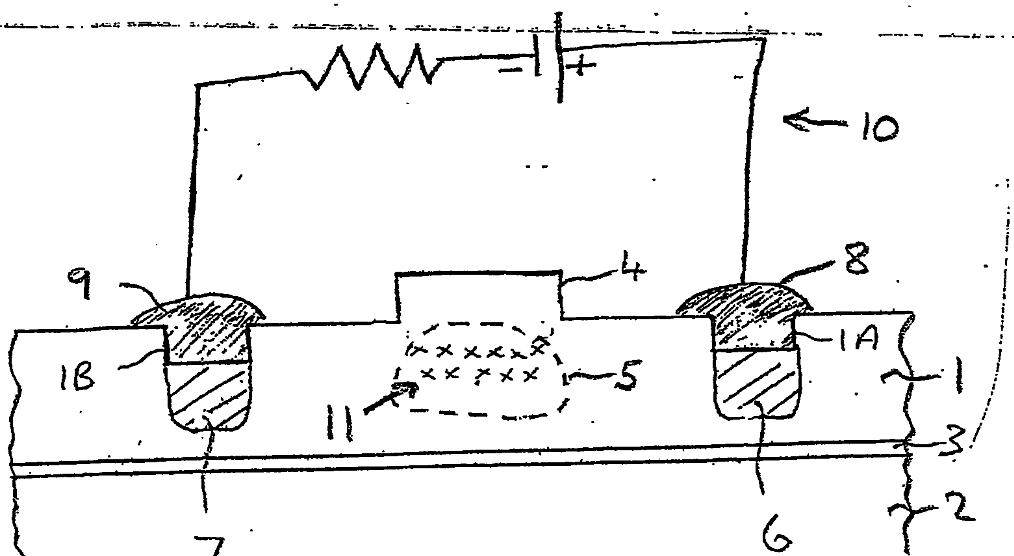

FIG. 1

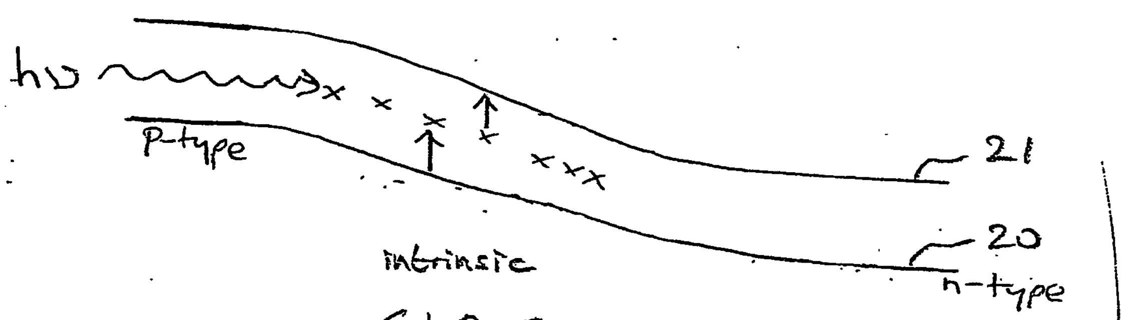

FIG. 2

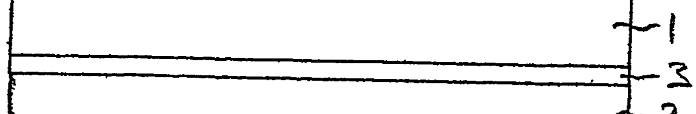

FIG. 3A

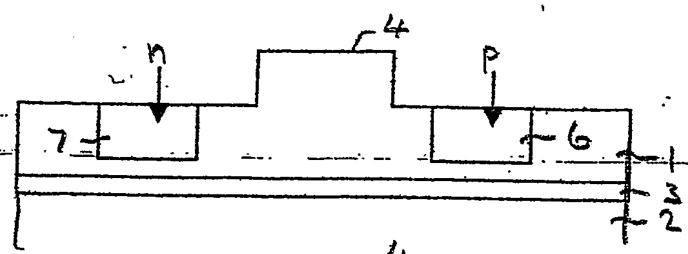

FIG3B

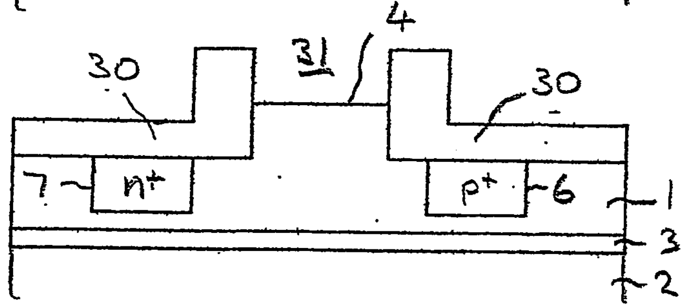

FIG3C

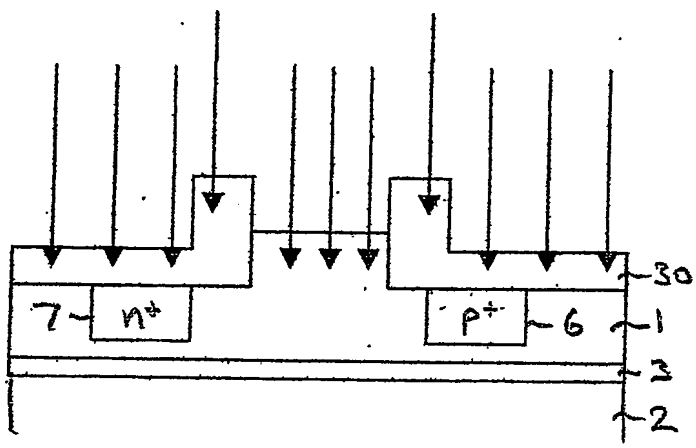

FIG3D

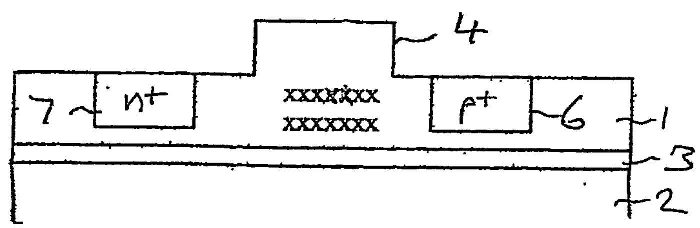

FIG3E

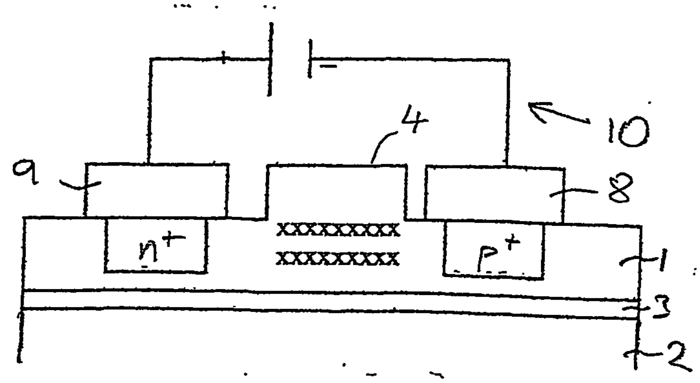

FIG3F